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HTS/LTS HYBRID HIGH FIELD SUPERCONDUCTING MAGNET DESIGNS FOR THE PROPOSED 100 TeV PROTON COLLIDERS*

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Abstract

Proposed proton-proton colliders with a center-of-mass energy up to 100 TeV in a tunnel of desired size require the dipole magnets to be of very high field—20 teslas in some proposals. This field is beyond the limit of present conventional Low Temperature Superconductors (LTS) and requires using High Temperature Superconductors (HTS). The preliminary magnetic design presented in this paper is an HTS/LTS hybrid design with high strength HTS tape used in higher field regions and less expensive LTS in lower field regions, with a goal of optimizing the performance while reducing the cost. A major concern in the magnets built with the HTS tape is the large field errors associated with the conductor magnetization. The strategy presented here aims to reduce those errors considerably. This paper also presents a proof-of-principle design and program to experimentally evaluate that concept.

INTRODUCTION

As a part of a recently funded Phase II Small Business Technology Transfer (STTR) award [1] by the U.S. Department of Energy (DOE), Particle Beam Lasers, Inc. (PBL), Brookhaven National Laboratory (BNL) and Energy to Power Solutions (E2P) are developing designs and technologies for accelerator magnets of very high field (20 T or more). Phase I of this STTR demonstrated this technology in a preliminary way [2]. To reduce cost, HTS/LTS hybrid designs are being examined. HTS is used in higher field regions, and conventional LTS in lower field regions. The designs are based on second generation (2G) ReBCO HTS tape with Hastelloy substrate, chosen primarily for its high strength and its ability to deal with large stresses. ReBCO is available in long lengths from several vendors around the world. The hybrid design presented here is based on a technique that is expected to keep the persistent current-induced harmonics to a manageable level despite the tape geometry of the conductor. These designs and technologies could be used in the proposed Future Circular Collider (FCC) at CERN [3] and/or the proposed Super proton-proton Collider (SppC) in China [4].

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MAGNETIC DESIGN

A preliminary magnetic design of a 21 T, 50 mm aperture HTS/LTS hybrid design is presented in Fig. 1, showing one quadrant of a magnet. The field contours and types of conductor used are shown in Fig. 2. Key design parameters are listed in Table 1. The block design allows easy conductor block segmentation and furthermore better magnetic and mechanical optimization. A segmented mechanical structure intercepts accumulated forces, similar to that used in an earlier design [5]. The space between the blocks will be adjusted to allow for an adequate space for structure. Ends will be lifted up to clear the bore or have an overpass/underpass configuration [6]. LTS coils will be simple and flat. Only the ends of a few HTS coils will need to be lifted to clear the bore in a common coil configuration [7].

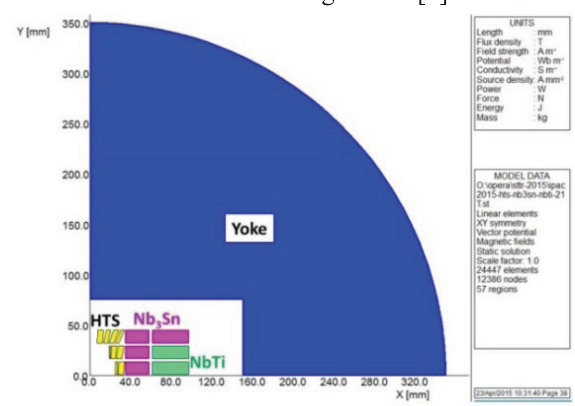

Figure 1: Quadrant of the magnetic model consisting of HTS, Nb_3Sn and NbTi (LTS) coil blocks and iron yoke.

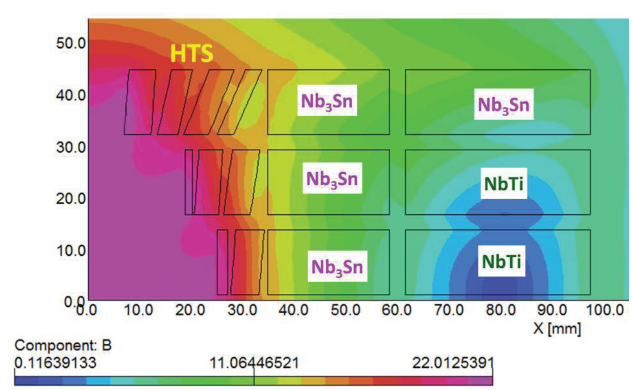

Figure 2: Field contours at central field of 21 T. Blocks with x<35mm use HTS (ReBCO tape); those with x>35mm use Nb3Sn or NbTi (LTS).

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Table 1: Preliminary Key Design Parameters

Nominal Field	21 T
Aperture	50 mm
Conductor Type	HTS: ReBCO, Nb_3Sn, NbTi
Conductor Width	12.5 mm (All)
Peak Field @21 T	21.9 T (HTS), 13.8 T (Nb_3Sn), 8.3 T (NbTi)
Overall Current Density in Coil @21 T	1000 A/mm^2 (HTS), 500 A/mm^2 (Nb_3Sn & NbTi)
Conductor Area per Quadrant	450 mm^2 (HTS), 1328 mm^2 (Nb_3Sn), 895 (NbTi) mm^2
Stored Energy	2.3 MJ/meter
Forces per quadrant (Horizontal, Vertical)	HTS: (7.5 MN/m, -1.2 MN/m) LTS: (4.4 MN/m, -4.6 MN/m)
Stresses (Horizontal, Vertical)	HTS: (200 MPa, < -40 MPa) LTS: (120 MPa, -80 MPa)
Yoke o.d., Aperture (Horizontal, Vertical)	700 mm (o.d.) 300 mm (H), 150 mm (V)

TECHNIQUE TO REDUCE FIELD ERRORS IN MAGNETS WITH HTS TAPE

Persistent Current-induced Harmonics

The persistent currents that give rise to magnetic field distortions are proportional to the dimension that is perpendicular to the field lines. Conventional cosine theta designs and common coil designs [7] that use tape are expected to generate large error harmonics, because the wide side of the tape predominately remains perpendicular to the field [8-10].

Design Strategy to Reduce Field Errors

The width of coated superconductor in HTS tape is typically 4 mm to 12 mm, but the thickness is only about a micron. The conductor magnetization effects, and hence the persistent current-induced field errors, could be several orders of magnitude lower if the narrow, not the wide, side of the tape were to intercept the field..

In a properly optimized HTS/LTS hybrid design, it is possible to align the HTS tape within five degrees or so to the field lines. LTS (Nb_3Sn and NbTi), are composed of fine filaments and do not create similarly large field distortions.

The use of this technique is illustrated in Fig. 3 for the cross-section presented in Fig. 1 and 2. The design is optimized so that the perpendicular component of the field covers minimum surface area of the tape. It has been shown that such alignment significantly reduces the amount of HTS required [11]. The design in Fig. 3 is based on ~12.5 mm wide conductor for both HTS tape and LTS cable. HTS tape from SuperPower [12] can have a bend diameter as small as 11 mm. Danfysik has made an R&D HTS dipole [13] using ~4 mm wide tape.

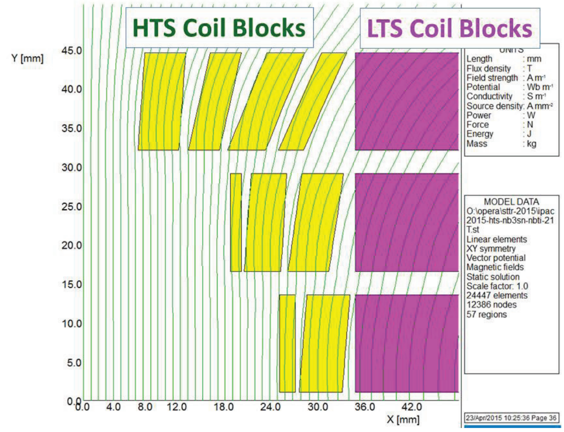

Figure 3: HTS (yellow, lighter shade) and LTS (pink, darker shade) coil blocks. HTS coil blocks are optimized to be parallel the field lines in a 50 mm aperture dipole.

Figure 4: 10 T Nb_3Sn common coil dipole DCC017 with a large open space for testing insert coil(s).

Proof-of-Principle Demonstration Magnet

BNL has a fully tested, Nb_3Sn common coil 2-in-1 dipole DCC017 (Fig. 4) that reached a bore field of over 10 T [7] and that has a large opening (~30 mm horizontal and ~220 mm vertical). This provides a unique opportunity to experimentally evaluate the validity of the proposed technique. In the proposed PBL/BNL/E2P proof-of-principle test, a set of HTS tape coils will be built, installed inside DCC017 and tested in the 10 T background field. These HTS coils would be designed such that field lines are perpendicular to the narrow side of the tape (see Fig. 5). This is expected to be a low-cost, fast turnaround proof-of-principle demonstration because DCC017 is designed such that it requires no disassembly and reassembly for insert coil testing.

If successful, the magnet will not only demonstrate the validity of the concept but will also constitute an HTS/LTS hybrid magnet producing a field of ~14 T. A current density of 1000 A/mm^2 is assumed in HTS coils, because the field is primarily parallel to the wide side of

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the tape. A proper structure/filler will be included inside the HTS coil and between the HTS and LTS coils to contain the Lorentz forces. Hall probes will be placed inside the assembly to make field measurements.

The HTS coil structure will be made such that it can be installed so that 90° rotation is possible (worst case with the field perpendicular). Fig. 6 shows a simplified model of two HTS coils placed in the two apertures of the common coil magnet DCC017. The HTS coils will be installed in two orientations – favorable and unfavorable.

Another configuration for HTS insert coils is the common coil design with the tape aligned in the favorable direction and large bend radii aiding the ends.

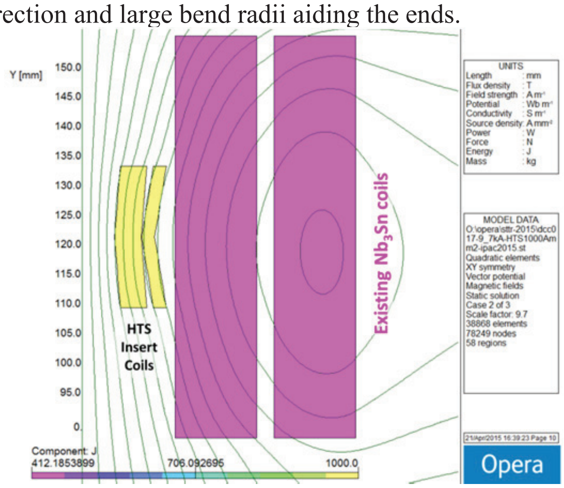

Figure 5: Field lines in one half of one aperture in the proof-of-principle dipole. HTS tape coil blocks (yellow, light shade), are aligned with the field lines and inserted within the aperture of the Nb_3Sn coils (pink, darker).

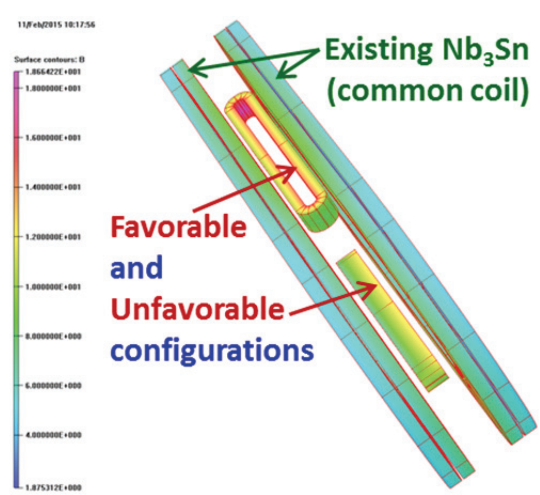

Figure 6: Simplified magnetic model (only coils shown) of two set of HTS insert coils placed between Nb_3Sn coils of magnet DCC017.

HIGH CURRENT OPTION

High current HTS cables, rather than a single tape carrying less than 1 kA, are preferred for large scale accelerator magnet applications. Use of a single 12 mm wide tape in a field parallel direction already allows over 3 kA of current carrying capability and over 5 kA expected in the near future. Multi-tape configurations are also available and were examined in Phase I of this program [2]. We are exploring a variety of configurations with three to four tapes which would allow current in HTS coils to be over 10 kA and allowing serial connections with the LTS coils. An important benefit of the wide multi-tape configuration is that current sharing would guard against a local weak or hot spot limiting the performance of the entire magnet, thus making the design more robust.

SUMMARY

Magnet design strategies have been developed for high field HTS/LTS hybrid magnets. These strategies should improve the technical performance and reduce the cost. Making the magnetic field perpendicular to the narrow side of HTS tape should reduce persistent-current induced harmonics by over an order of magnitude. As a part of the PBL/BNL/E2P Phase II STTR, this concept will be tested in a proof-of-principle magnet. The same orientation significantly reduces the amount of conductor required by increasing the current-carrying capability of ReBCO tape and hence should significantly reduce the net cost of HTS in a hybrid magnet.

REFERENCES

[1] http://science.energy.gov/sbir/awards/
[2] R. Gupta, et al., "Hybrid High Field Cosine Theta Accelerator Magnet R&D with Second Generation HTS," Applied Superconductivity Conference, Charlotte, NC, August 10-15, 2014.
[3] http://cern.ch/fcc
[4] http://cepc.ihep.ac.cn/preCDR/main_preCDR.pdf
[5] R. Gupta, et al., "Optimization of Open Mid-plane Dipole Design for LHC IR Upgrade," 2005 Particle Accelerator Conference, Knoxville, TN, USA (2005).
[6] R. Gupta, et al., "Next Generation IR Magnets for Hadron Colliders," 2002 Applied Superc. Conf.
[7] R. Gupta, et al., "React & Wind Nb_3Sn Common Coil Dipole," 2006 Applied Superconductivity Conference.
[8] N. Amemiya, et al., "Temporal behaviour of multipole components of the magnetic field in a small dipole magnet wound with coated conductors," 2015 Supercond. Sci. Technol. 28 035003.
[9] Y. Iwasa, "Case Studies in Superconducting Magnets," 2nd Ed. (Springer, 2009).
[10] C.P. Bean: "Magnetization of hard superconductors," Phys. Rev. Lett. 8, 250 (1962).
[11] J. van Nugteren, et al., "Study of a 5 T Research Dipole Insert-Magnet using an Anisotropic ReBCO Roebel Cable," IEEE Transactions on Applied Superconductivity, 15 October 2014.
[12] http://www.superpower-inc.com/
[13] N. Zangenbery, et al., "Conduction Cooled High Temperature Superconducting Dipole Magnet for Accelerator Applications," IEEE Trans. Appl. Supercond. 22 (2012) 4004004.